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Preboreal climate oscillations in Europe: Wiggle-match dating and synthesis of Dutch high-resolution multi-proxy records

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Abstract

In order to compare environmental and inferred climatic change during the Preboreal in The Netherlands, five terrestrial records were analysed. Detailed multi-proxy analyses including microfossils (e.g., pollen, spores, algae, and fungal spores), macroremains (e.g., seeds, fruits, wood, mosses, etc.), and loss on ignition measurements were carried out with high temporal resolution. To link the five Preboreal records, accurate chronologies were produced by AMS ^{14}C wiggle-match dating. The Dutch records show that following the Lateglacial/Holocene climate warming, birch woodlands expanded between 11,530 and 11,500 cal BP during the Friesland Phase of the Preboreal. After the Friesland Phase, two distinct climatic shifts could be inferred: (1) around 11,430–11,350 cal BP the expansion of birch forests was interrupted by a dry continental phase with open grassland vegetation, the Rammelbeek Phase. This phase was coeval with the coldest part of the Preboreal oscillation (PBO) as observed in the $\delta^{18}O$ record of the Greenland ice-core records and has been attributed to a large meltwater flux that resulted in a temporary decrease of the thermohaline circulation in the North Atlantic. (2) At the start of the Late Preboreal, between 11,270 and 11,210 cal BP, a sudden shift to a more humid climate occurred and birch forests expanded again. A simultaneous increase in the cosmogenic nuclides ^{14}C and ^{10}Be suggests that these changes in climate and vegetation were forced by a sudden decline in solar activity. Expansion of pine occurred during the later part of the Late Preboreal. At the onset of the Boreal, between 10,770 and 10,700 cal BP, dense woodlands with hazel, oak, elm and pine started to develop in The Netherlands.

1. Introduction

Lacustrine sediments and peat deposits are valuable archives for the study of past climate change. In order to compare environmental and inferred climatic change during the Preboreal in The Netherlands, five terrestrial records (Lochem-Ampsen, Borchert, Zutphen, Kreekrak and Haelen) were selected for high-resolution multi-proxy analyses. Detailed botanical and zoological analyses (including pollen, spores, other microfossils and macroremains) and additional geochemical analyses (loss on ignition (LOI)), enables the comparison between different climate proxy records. The palynological record will mainly show the regional vegetation development, while other microfossils, macroremains and geochemical data will reflect the development of local environmental conditions. In order to record environmental response to short climatic oscillations, palaeoecological analyses were carried out with a high-resolution in time, i.e., vertical sample distance 1 cm, encompassing max. 20 years.

For linking the climatic signals from the different locations, calendar year chronologies are of crucial importance. Precise dating is essential for the study of leads and lags and the potential causes and effects within the climate system. However, as a consequence of

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atmospheric ^{14}C variations in the past, early Holocene calibration of ^{14}C dates is hampered by the presence of two large ^{14}C plateaux, respectively, at ca 10,000–9900 and 9600–9500 BP. No precise calendar age chronology could therefore be obtained from records that covered the Lateglacial/Holocene transition and the Late Preboreal. In order to obtain a more accurate chronology, AMS ^{14}C wiggle-match dating (WMD) of terrestrial macrofossils was applied to the five Preboreal sites. A WMD-based chronology enables the comparison between chronologies from various palaeoclimate archives, such as the palaeobotanical record (pollen, macroremains, and others), the dendrochronological record ($\Delta^{14}C$) and the Greenland ice-core records ($\delta^{18}O$, ^{10}Be).

In this paper, we will discuss environmental and inferred climatic change as recorded in five Preboreal sites from The Netherlands. Furthermore, climate forcing factors and earlier suggested relations (see van der Plicht et al., 2004) between climate change in NW Europe and Greenland, solar variability (as evidenced by two cosmogenic isotope proxies ^{14}C and ^{10}Be) and fluctuations in the atmospheric CO_2 concentration will be evaluated.

2. Study area

The vegetation development in The Netherlands during the Preboreal was strongly influenced by the geomorphology of the landscape (Hoek, 1997a, b). To investigate the environmental response of short climatic oscillations during the Preboreal, five sites were selected in different geomorphological landscape regions (Hoek, 1997b) (Fig. 1a and c). The Borchert and Lochem-Ampsen sites represent the eastern coversand area. The Zutphen record was collected at the transition between this coversand area and the northern river region formed by the River IJssel. The Haelen and Kreekrak sites represent different parts of the river region, i.e., the southeastern part formed by the River Maas and the southwestern part formed by the River Schelde, respectively.

Preboreal records from The Netherlands are often hampered by hiatuses. In many of the Dutch palynological records the drier Rammelbeek Phase is absent or not recognisable (see low number of records in Fig. 1b). This is probably related to the lower groundwater levels during this phase (Hoek, 1997a; Hoek and Bohncke, 2002). Preboreal sites with more complete records seem to be concentrated in river valleys (Fig. 1c). For the present study therefore all five records were collected from former river channels.

2.1. Lochem-Ampsen

The Lochem-Ampsen site (52°10′02″N; 06°25′32″E) is located directly east of the Huize Beukestein estate, north of Lochem, eastern Netherlands (Fig. 1c). The site is positioned in the extensive eastern coversand region of The Netherlands. This area is characterised by thick layers of coversand that were formed during the Weichselian Pleniglacial and Lateglacial periods (van der Hammen and Wijmstra, 1971; Schwan, 1988). The Lochem-Ampsen record was collected from a basin-shaped depression, probably a former river channel in which peat was formed. The vegetation history of the site will be published by Bos et al. (in preparation a).

2.2. Borchert

The Borchert sequence (52°22′48″N; 6°59′34″E) was sampled during an archaeological excavation in the northwestern part of Denekamp, eastern Netherlands (Fig. 1c). At the start of the Younger Dryas this coversand area became divided into several isolated parts by branches of the former Dinkel River drainage system (van der Hammen, 1971). During the late Younger Dryas one of these river channels became abandoned and sedimentation started under lacustrine conditions. Accumulation of gyttja was followed by formation of peat. Sedimentation continued up to ca 3400 BP. The detailed palynological, palaeobotanical and palaeoclimatological record was published by van Geel et al. (1981). An atmospheric CO_2 curve based on stomatal frequency signatures of fossil birch leaves from the Early Holocene part of the record was illustrated by Wagner et al. (1999). Originally the record was dated using the conventional radiocarbon method with a limited number of bulk peat samples. Recently a WMD-based chronology based on AMS dates of terrestrial material was obtained (van der Plicht et al., 2004).

2.3. Zutphen

The Zutphen-Ooijerhoek site (52°07′36″N; 06°13′24″E), eastern Netherlands, is located at the transition between the northeastern coversand region in the east and the stream valley of the River IJssel in the west (Fig. 1c). In the transitional zone between the coversand area and the IJssel valley, numerous river dunes were formed during the late Weichselian and Early Holocene. One of these dunes, probably formed during the Younger Dryas, was bordered on the southeast by a ca 200 m wide river valley, in which at present the River Ooijerhoeksche Laak is flowing. During the Early Holocene a river cut into the older river sediments and in an abandoned channel a Late Preboreal organic deposit was formed. Later during the Holocene, the river valley was overlain by a thick layer of fluvial deposits of the Ooijerhoekse Laak and IJssel Rivers. The Early Holocene vegetation development and archaeological investigations, which focus on the presence and disappearance of early Mesolithic habitation, are described by Bos et al. (2005a).

2.4. Kreekrak

The Kreekrak site (51°26′21″N; 4°14′25″E) is located near the eastern edge of the coastal plain in the province of

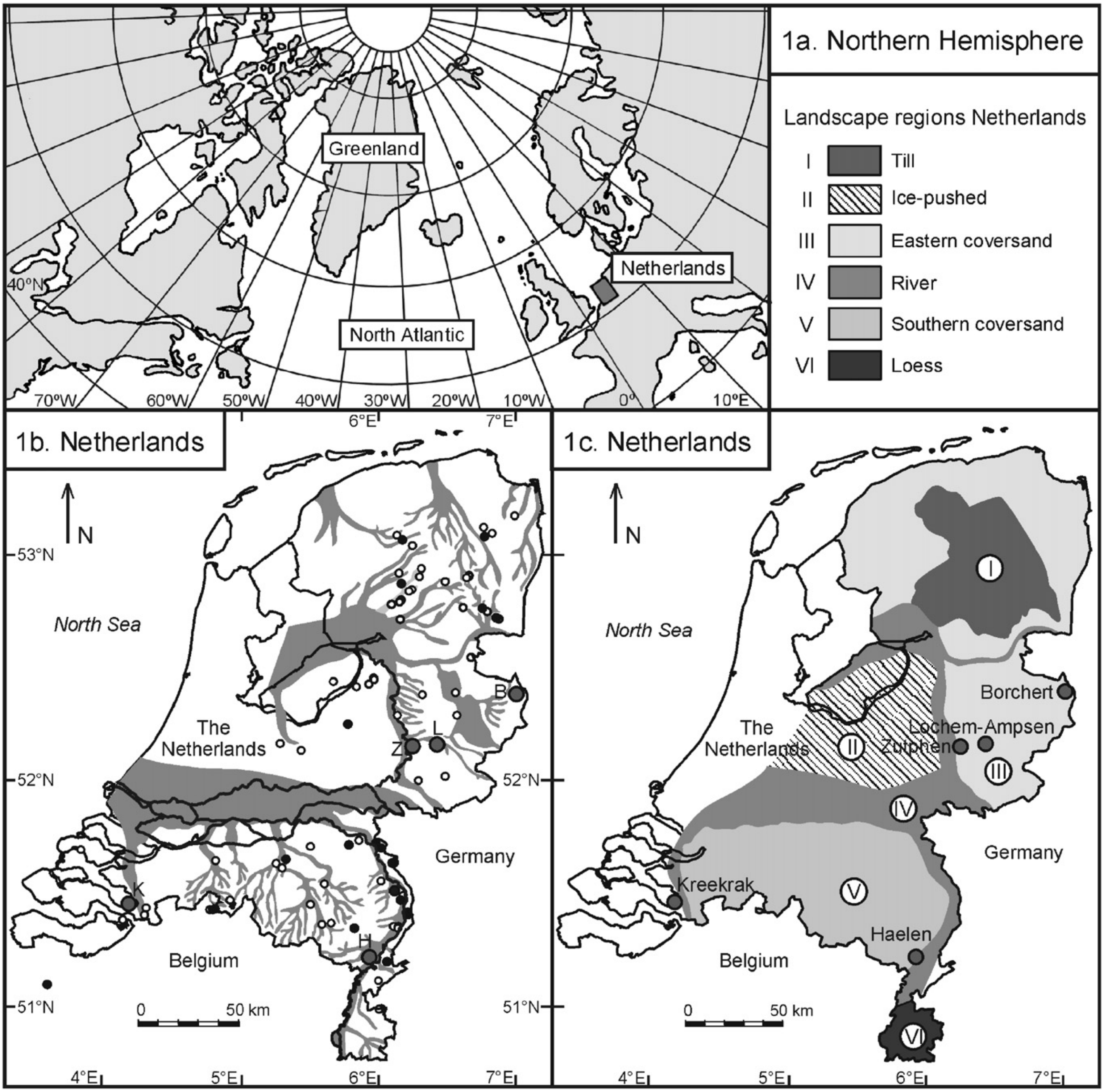

Fig. 1. Location maps: (a) Northern Hemisphere, with the location of The Netherlands; (b) distribution of Preboreal records (○) and those with a Rammelbeek Phase (●) and the Lateglacial river and brook valleys in The Netherlands and Belgium. L = Lochem-Ampsen, B = Borchert, Z = Zutphen, K = Kreekrak, H = Haelen; and (c) location of the five sites in the geomorphological landscape regions of The Netherlands (Hoek, 1997b).

Zeeland (Fig. 1c). The coastal plain is about 50 km wide and is bordered on the eastern side by a pronounced escarpment up to 20 m high, consisting mainly of Early Pleistocene (Tiglian) deposits (Kasse, 1988). At the foot of the Tiglian escarpment, the palaeovalley of the River Schelde is cut into the gently undulating sandy substratum. On its western side, the palaeovalley is bordered by a north–south trending ridge in the Pleistocene topography, the Rilland ridge. The Kreekrak borehole was drilled a few kilometres west of the Schelde palaeovalley between the Rilland ridge and the Tiglian escarpment. Cross-sections through the area show that the Kreekrak lake was located at a relatively deep level (ca −13.00 m NAP) in relation to the depth of the palaeovalley itself. The Kreekrak lake was probably a residual channel of the Lateglacial River Schelde. The detailed palaeoecological and geochemical records are described by Bos et al. (2005b).

2.5. Haelen

The Haelen record (51°13′55″N; 5°58′51″E) was collected from a residual channel of the River Maas near Roermond, southeastern Netherlands (Fig. 1c). The former river channel had eroded westward far into the southern coversand region and was originally probably ca 10 m deep and 80 m wide. The channel became abandoned at the end of the Younger Dryas and sedimentation started under lacustrine conditions. Accumulation of gyttja was followed during the Boreal by formation of peat. The vegetation development and WMD chronology will be published by Bos et al. (in preparation b).

3. Methods

3.1. Botanical analysis

From the sediment cores, subsamples were taken at 1 cm intervals for high-resolution microfossil (pollen, spores, fungi, algae, etc.), and macroremain (seeds, fruits, wood, mosses, etc.), analyses and LOI analysis. Microfossil samples were collected using a small corer of defined volume (~280 mm^3) and prepared following Faegri and Iversen (1989) in addition with heavy liquid separation. Sieving was carried out using a 215 μm sieve. *Lycopodium* spores were added to calculate pollen concentrations. The residues were mounted in glycerine. A Leica light microscope (magnification 400× and 1000×) was used for pollen counting. Preservation in general was excellent. Pollen types were identified by comparison with modern reference material and identification keys of Moore et al. (1991) and the NEPF Vols. I–VIIII (Punt et al., 1976–2003). Nomenclature follows these keys. Other microfossils were identified using Komárek and Jankovská (2001), van Geel (1978, 2001), and van Geel et al. (1981, 1983, 1989, 2003).

Macroremain samples were boiled in 5% KOH for ca 5 min and washed over a 75–80 μm sieve. Macroremains were picked out from the recovered fraction and stored at 4 °C. For screening and selection a Leica dissection microscope (magnification of 8–100×) was used. Plant macrofossil identifications were made by comparison with modern reference material and identification keys of Berggren (1969, 1981), Anderberg (1994), Beijerinck (1947), Nilsson and Hjelmqvist (1967), and Schweingruber (1978). Nomenclature follows van der Meijden (1996).

Microfossil and macroremain diagrams were constructed using the Tilia, Tilia.graph and Tg.view computer programs (Grimm, 1991–2004). In the present study only selections of taxa are shown. Combined arboreal pollen (AP) and non-arboreal pollen (NAP) totals were employed for percentage calculations. Pollen and spores of the local aquatic- or mire vegetation (inclusive Cyperaceae) and redeposited palynomorphs of thermophilous taxa were excluded (compare Janssen, 1973; Bos, 1998). Inwash of redeposited palynomorphs of thermophilous taxa often occurred in the more minerogenic lower part of the records. Zonation of the diagrams is based on changes in the AP/NAP ratio and trends in the percentages of arboreal taxa that dominate Lateglacial–Early Holocene pollen records of NW Europe.

Palaeotemperature estimates based on the botanical taxa were made using the climate indicator plant species method (sensu Iversen, 1954; Kolstrup, 1980). Table 1 shows selected plant taxa and their summer temperature requirements.

3.2. AMS ^{14}C wiggle-match dating

In order to provide an accurate chronology for the Preboreal records, samples of organic material reflecting atmospheric ^{14}C concentrations, such as seeds and fruits from terrestrial plants were selected for radiocarbon dating. Radiocarbon dates were converted into calendar years by using the visual WMD method (e.g., van Geel and Mook, 1989; Kilian et al., 2000; Speranza et al., 2000; Mauquoy et al., 2002; Blaauw et al., 2003, 2004). In this method, the wiggles in the ^{14}C calibration curve are used to obtain a more accurate chronology. High-resolution series of uncalibrated AMS radiocarbon dates are matched to the ^{14}C IntCal04 calibration curve (Reimer et al., 2004) by using the stratigraphical position of the dates (Figs. 7–11). The WMD method is especially suitable for the steep parts of the calibration curve, which correspond to periods of rapidly changing atmospheric ^{14}C concentrations. Prior to the WMD, some of the records had to be divided into two or more sections based on sedimentological changes and/or changes in the accumulation rate (e.g., Lochem-Ampsen, Kreekrak), or on the presence of a hiatus (e.g., Kreekrak). Subsets of ^{14}C dates from these sections were then wiggle-matched separately (Figs. 7 and 10). Absolute ages are reported in cal BP, i.e., calibrated or calendar age relative to 1950.

3.3. Loss on ignition analysis

To provide a measure of the organic C content, LOI analysis was carried out on samples from the Kreekrak, Lochem-Ampsen and Haelen records. Sediment samples of a few cm^3 were dried overnight in crucibles at 105 °C to remove any moisture, cooled in a dessicator and weighted. The sample plus crucible were then put into the furnace at 550 °C (e.g., Kreekrak, Haelen) or 450 °C (e.g., Lochem-Ampsen) for 4 h for the ashing of the organic matter. Once the ashing was completed the crucibles were cooled in a dessicator and re-weighed to provide a measure of LOI.

4. Results

4.1. Botanical results

Based on changes in the forest composition (AP) and herbaceous vegetation (NAP), the Preboreal biozone in The Netherlands, is subdivided into a Friesland Phase, a Rammelbeek Phase and the Late Preboreal. In the pollen diagrams of the five Dutch Preboreal sites, this subdivision of the Preboreal is clearly recognisable (Figs. 2–6). The Lochem-Ampsen, Borchert, Kreekrak

Table 1
Temperature indicator plant taxa present at the investigated sites, their minimum mean July temperatures (MMJT) and reference

Plant taxon	MMJT (°C)	Reference	YD	FP	RP	LP	BO
Polygonum viviparum	5	Kolstrup (1980)	P		P		
Trollius europaeus	6–7	Kolstrup (1980)		P			P
Betula nana	7	Brinkkemper et al. (1987); Ran (1990)	P, M	P, M	P		
Calluna vulgaris	7	Kolstrup (1979, 1980)	P	P	P	P	
Epilobium angustifolium	7	Brinkkemper et al. (1987)	P	P	P	P	
Selaginella selaginoides	7	Kolstrup (1979, 1980)	P		P		
Empetrum	7.7	Vorren (1978)	P, M	P	P		
Caltha palustris	8	Kolstrup (1980)			P		
Carex rostrata	8	Brinkkemper et al. (1987)	M	M	M		M
Juniperus communis	8	Kolstrup (1980)	P	P	P	P	
Filipendula ulmaria	8	Brinkkemper et al. (1987)	P, M	P, M	P, M	P, M	P
Menyanthes trifoliata	8	Kolstrup (1979, 1980)	P	P, M	P, M	P	P, M
Potentilla palustris	8	Brinkkemper et al. (1987)		M			
Triglochin palustre	8	Kolstrup (1979, 1980)	P				
Urtica dioica	8	Kolstrup (1979, 1980)	P	P, M	P, M	P, M	P, M
Ranunculus flammula	8–9	Kolstrup (1979, 1980)		M			
Carex paniculata	9–10	Kolstrup (1979, 1980)				P	M
Myriophyllum alterniflorum	9–10	Kolstrup (1980)			P		
Sanguisorba officinalis	9–10	Kolstrup (1979, 1980)	P	P	P	P	P
Eleocharis palustris	10	Kolstrup (1980)					
Galium palustre	10	Vorren (1978)				M	
Myriophyllum spicatum	10	Kolstrup (1979, 1980)	P	P, M	P	P	P
Myriophyllum verticillatum	10	Kolstrup (1979, 1980)	P	P, M		P	P
Ranunculus Subgenus *Batrachium*	10	Brinkkemper et al. (1987)	M	M	M		M
Betula pubescens	>10	van der Hammen (1951)	P, M	P, M	P, M	P,M	P, M
Hippophae rhamnoides	11–12	Kolstrup (1979, 1980)	P	P	P		
Nuphar lutea	12	Kolstrup (1979, 1980)			P		M
Nymphaea alba	12	Kolstrup (1979, 1980)		P, M	P, M	P.M	P, M
Sanguisorba minor	12	Isarin and Bohncke (1999)	P	P	P	P	P
Pinus sylvestris	>12	Iversen (1954)				P,M	P, M
Carex pseudocyperus	13	Brinkkemper et al. (1987)				M	
Potamogeton mucronatus	13	Brinkkemper et al. (1987)	M		M		
Scirpus lacustris	13	Iversen (1954)		M	M		
Solanum dulcamara	13	Iversen (1954)		P, M	P, M	P, M	P
Typha latifolia	13	Isarin and Bohncke (1999)	P	P, M	P, M	P	P
Ceratophyllum demersum	13+15	Isarin and Bohncke (1999) Litt (1994)		M	M	M	M
Typha angustifolia	14	Kolstrup (1979, 1980)		P	P, M	P, M	P, M
Corylus avellana	15	Hoffmann et al. (1998)					P, M
Oenanthe aquatica	15	Iversen (1954)			M	M	M
Lycopus europaeus	16	Bell (1970)		M	M	M	M

YD = Younger Dryas, FP = Friesland Phase, RP = Rammelbeek Phase, LP = Late Preboreal, BO = Boreal, P = Pollen, M = Macrofossil.

and Haelen diagrams all cover the period between the late Younger Dryas and early Boreal. However, in the Kreekrak record the Late Preboreal is absent due to a hiatus. The Zutphen record only reflects the Late Preboreal.

In The Netherlands the last cold period before the start of the Holocene, the Younger Dryas, was characterised by an open landscape. During this period, the number of trees was low and especially during the later part of the Younger Dryas, Ericales (mainly *Empetrum*) formed an important element in the open vegetation (compare Hoek, 1997a, b). The relatively high Ericales values recorded in the Borchert deposits are a reflection of poor, acid soils, which have a larger abundance in the northeastern coversand area. The high Poaceae values in the Kreekrak and Haelen records can be regarded as typical for the river region.

The Friesland Phase (Behre, 1966) was characterised by a strong expansion of woodlands with birch, i.e., mainly *Betula pubescens* (van Geel et al., 1981; Bos et al., 2005b) and near Haelen and Kreekrak, also with *Populus*. The increase in birch values is often preceded by an increase in the *Juniperus* values. This *Juniperus* peak is more evident at sites surrounded by dry soils, such as in the coversand areas, e.g., Borchert, Lochem-Ampsen (cf. van der Hammen, 1951).

During the following Rammelbeek Phase (Behre 1966, 1978; Wijmstra and de Vin, 1971), all sites show high Poaceae percentages and a decrease in the birch values.

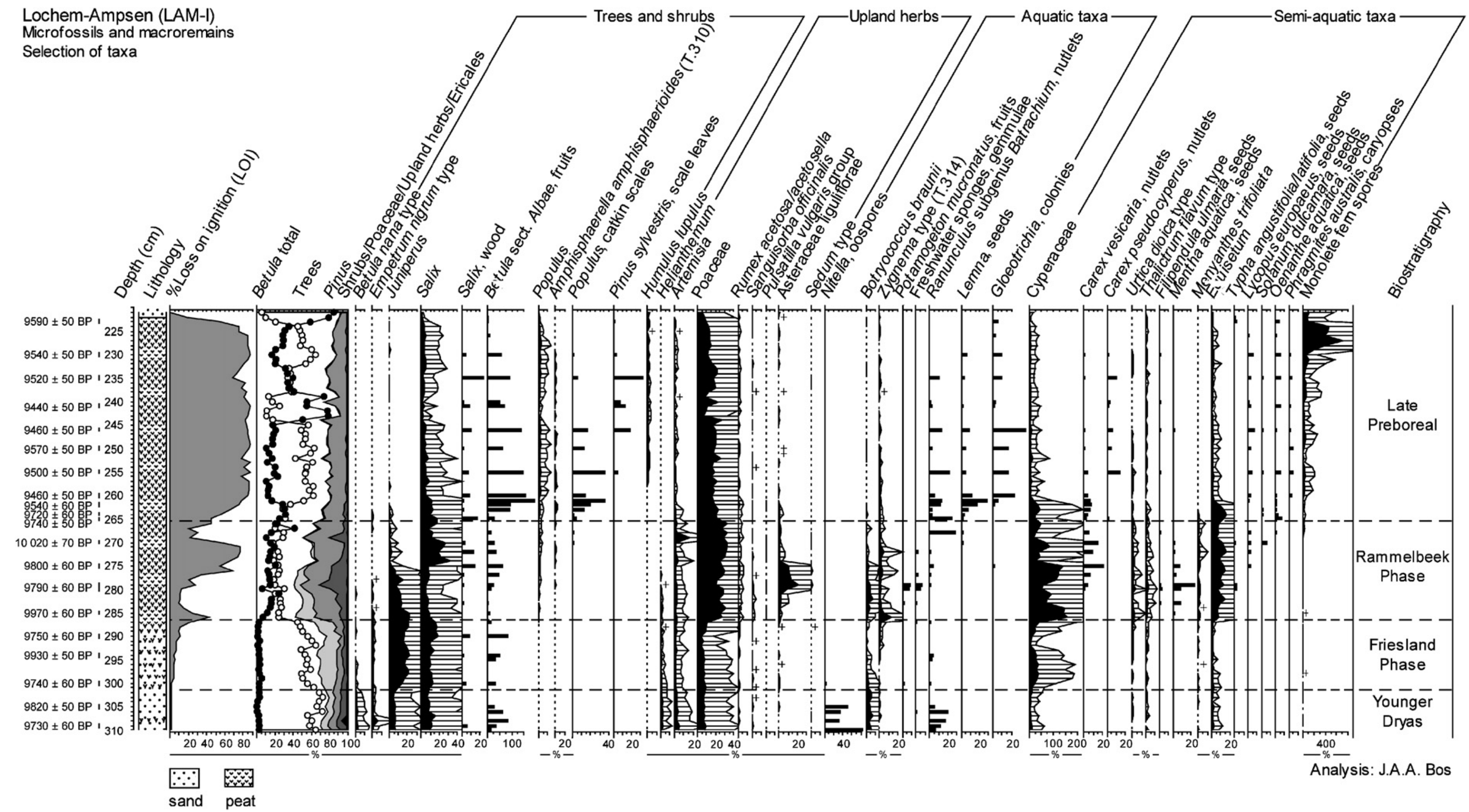

Fig. 2. Combined microfossil and macroremain diagram of the Lochem-Ampsen record. A selection of taxa is displayed. Microfossils (pollen, spores, etc.), are shown as curves (%), macroremains (fruits, seeds, wood, etc.), as histograms giving total amounts. Exaggeration of microfossil curves 5 ×. Not all radiocarbon dates are displayed.

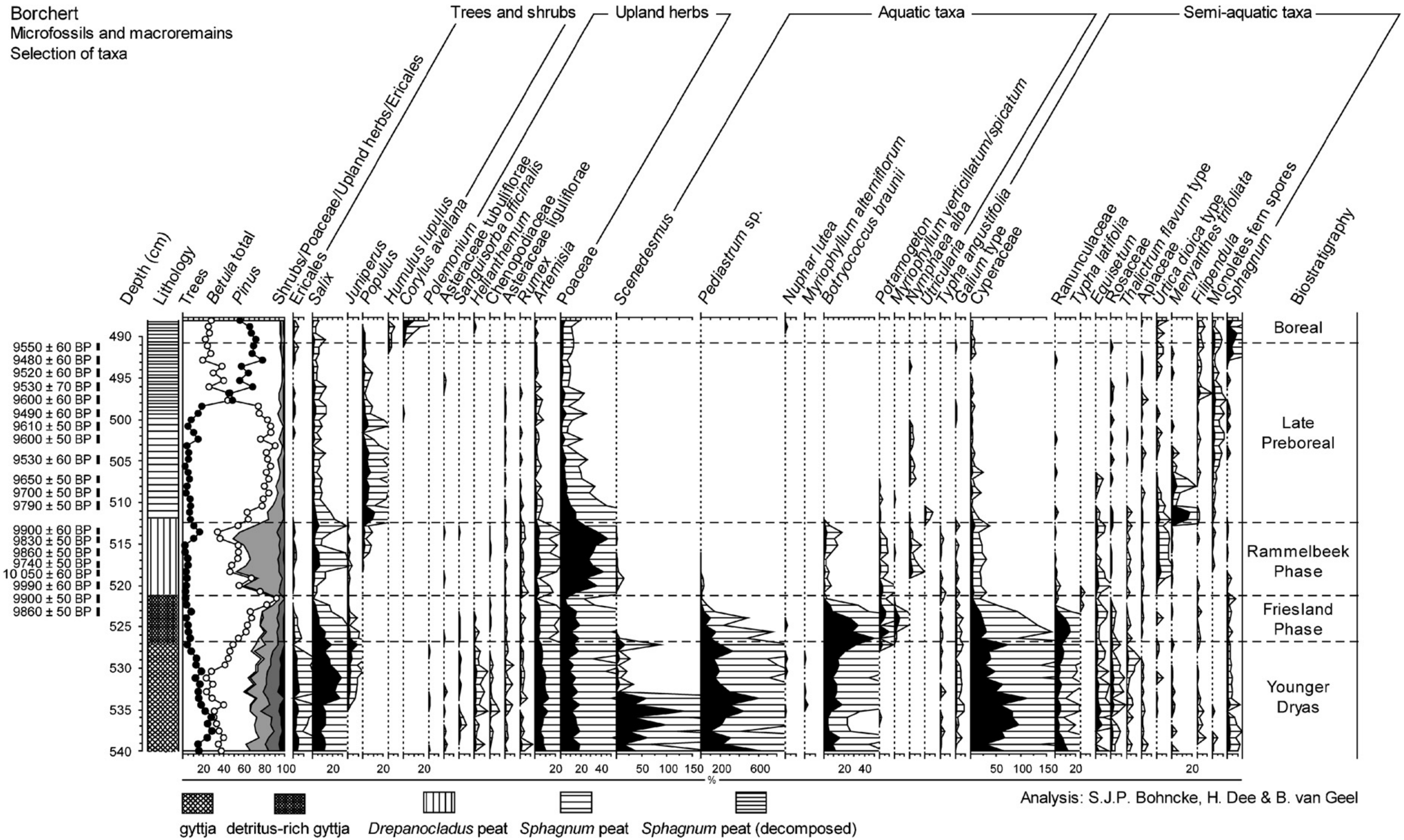

Fig. 3. Microfossil percentage diagram of the Borchert record (selection of taxa). Exaggeration of curves 5x. Not all radiocarbon dates are displayed.

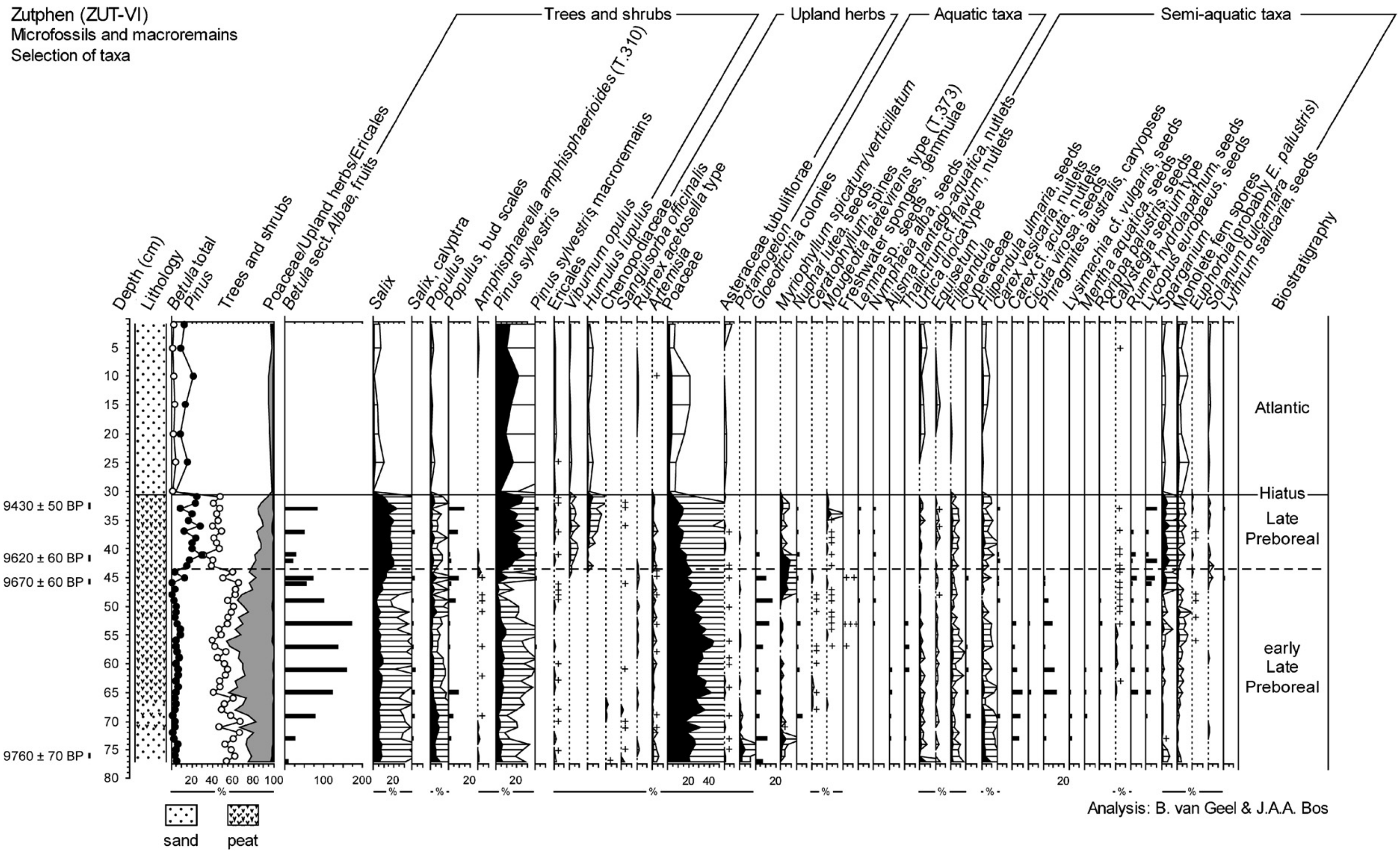

Fig. 4. Combined microfossil and macroremain diagram of the Zutphen record. A selection of taxa is displayed. Microfossils (pollen, spores, etc.), are shown as curves (%), macroremains (fruits, seeds, wood, etc.), as histograms giving total amounts. Exaggeration of microfossil curves 5 ×.

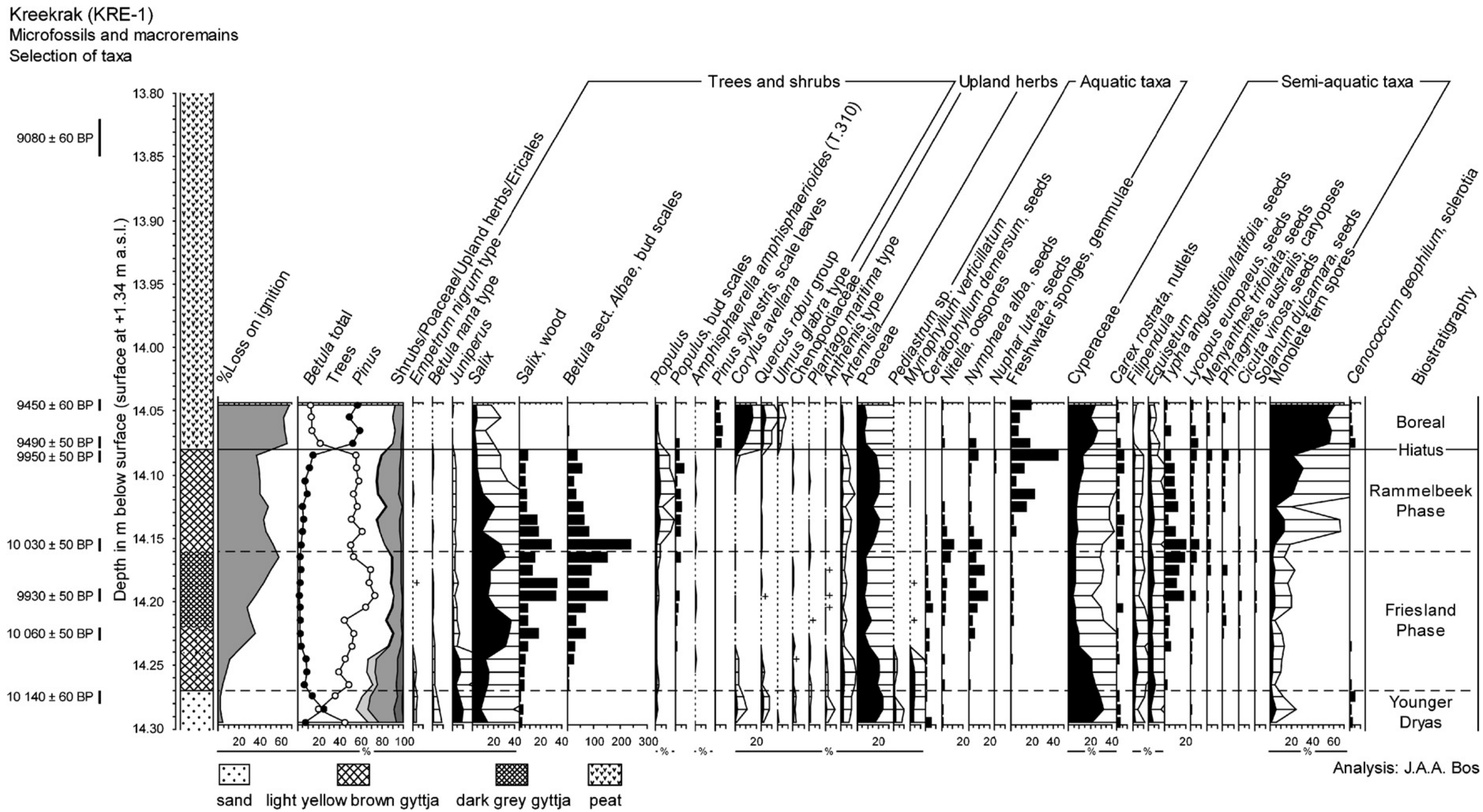

Fig. 5. Combined microfossil and macroremain diagram of the Kreekrak record. A selection of taxa is displayed. Microfossils (pollen, spores, etc.), are shown as curves (%), macroremains (fruits, seeds, wood, etc.), as histograms giving total amounts. Exaggeration of microfossil curves 5 ×.

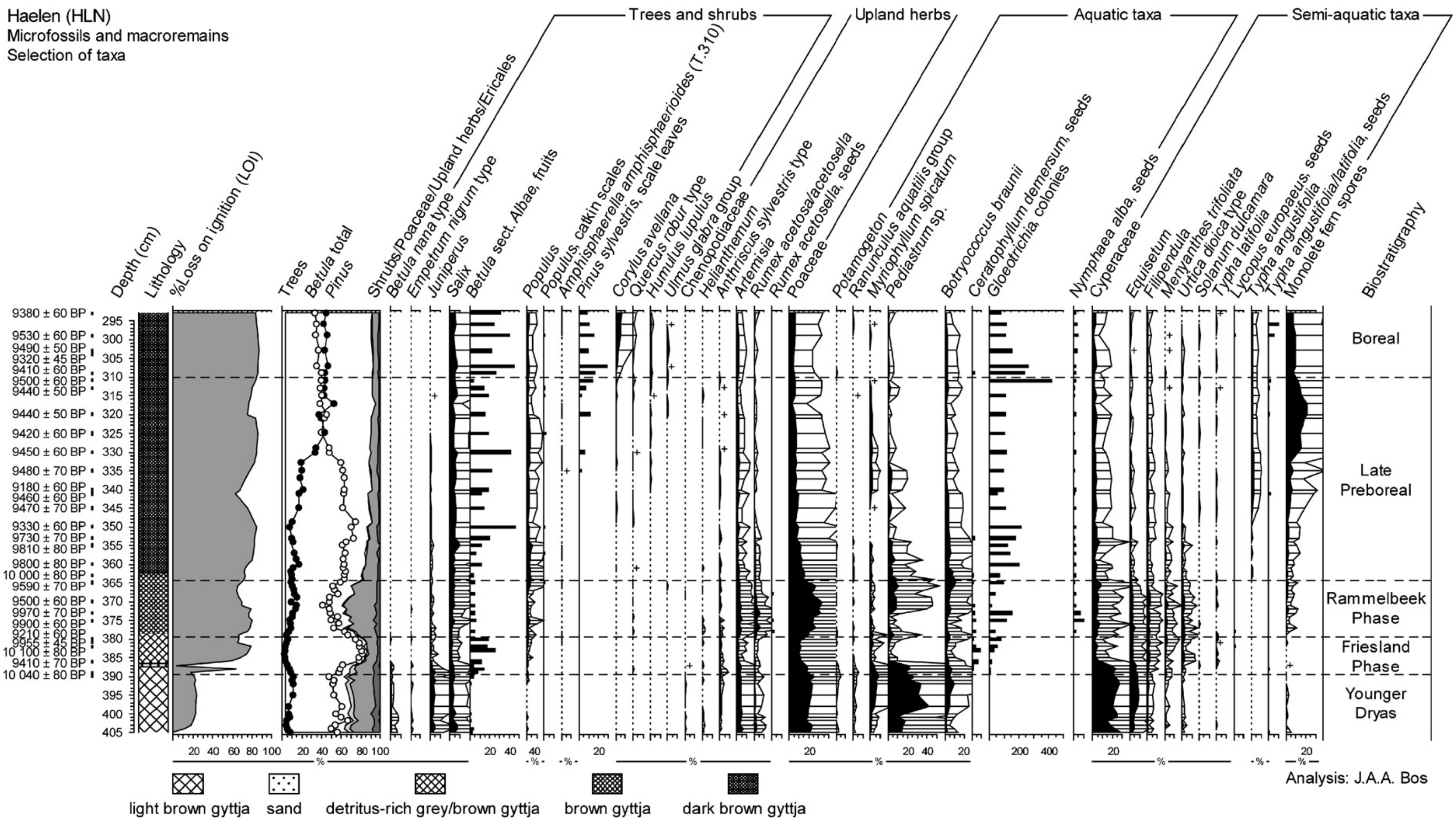

Fig. 6. Combined microfossil and macroremain diagram of the Haelen record. A selection of taxa is displayed. Microfossils (pollen, spores, etc.), are shown as curves (%), macroremains (fruits, seeds, wood, etc.), as histograms giving total amounts. Exaggeration of microfossil curves 5×.

This suggests a regional expansion of grasses, while forest development was interrupted. *Populus* appeared in the vegetation around the Borchert and Lochem-Ampsen sites. Based purely on the pollen record, the high Poaceae levels in the central part of the Zutphen diagram could have been interpreted as this grass-dominated phase. The macroremain record, however, points to the local presence of *Phragmites australis*.

The Rammelbeek Phase was followed by the Late Preboreal, a phase during which *Betula* and *Populus* woodlands expanded again. This is reflected in both the pollen and macroremain records. The presence of *Populus* is also indicated by numerous finds of ascospores of the parasitic fungus *Amphisphaerella amphisphaerioides* (van Geel and Aptroot, 2006). At some locations, local *Sphagnum* peat growth started (e.g., Borchert), while lakes (e.g., Haelen) showed higher water tables. *Pinus sylvestris* expanded during the later part of the Late Preboreal. Although pine had suffered considerably from the colder and wetter climate during the Younger Dryas, finds of pine macroremains at levels where pine pollen values are below 20% (i.e., Lochem-Ampsen, Haelen and Zutphen) indicate that the species was still present at sheltered locations in The Netherlands during the early Preboreal. In the Haelen and Borchert diagram pine pollen becomes dominant over birch. At the Haelen site, the pine values are only slightly higher than the birch values. In the Borchert diagram pine becomes dominant rapidly and reaches relatively high values. At Zutphen birch pollen remains dominant, while in the Lochem-Ampsen diagram the dominance of pine and birch alternate. The presence of pine macroremains (seeds, needles, etc.) at Lochem-Ampsen suggests that pine was growing close to the sample site. The high numbers of birch macroremains at Zutphen indicate local presence of birch, causing an overrepresentation of birch pollen. At the Haelen, Zutphen and Lochem-Ampsen sites, *Pinus* and *Humulus lupulus* arrive together. In the Borchert area, *Humulus* arrived later, at the start of the Boreal, together with *Corylus*. The relatively high Poaceae values at the Zutphen and Lochem-Ampsen sites reflect the (extra)local presence of *P. australis*.

The transition to the Boreal biozone is characterised by the immigration of *Corylus*. During the early Boreal, *Quercus* and *Ulmus* immigrate and woodlands started to develop with hazel, oak, elm and pine.

4.2. WMD results

All five Preboreal records were subdivided in biostratigraphic zones (Figs. 2–6). However, since biozones can be diachronous, absolute chronologies are necessary in order to compare the environmental and climatic signals.

4.2.1. Lochem-Ampsen

A series of 22 AMS ^{14}C samples (Table 2), ranging from the Younger Dryas to early Boreal, was measured. Apart from the presence of sandy peat in the lower part of the record, no major sedimentological changes are recorded. Therefore, the whole series of radiocarbon dates was initially wiggle-matched as one group, as if the sediment accumulation had been constant. This approach, however, failed to produce a sensible chronology. The botanical assemblages suggest that during the Rammelbeek Phase the accumulation rate decreased, which can be seen from a steady increase in the total microfossil concentration. A minimum in the total microfossil concentration at the onset of the Late Preboreal indicates that this was followed by a strong increase in the accumulation rate during the early Late Preboreal. Based on the interpretation of the concentration values, the record was divided into three sections, subsets 1–3. The lower 8 radiocarbon dates of subset 1 gave very young ^{14}C ages, which could not be matched to the IntCal04 ^{14}C calibration curve (Reimer et al., 2004). For the middle part of the record, subset 1, a low accumulation rate of 32 yr/cm was calculated. This series of 7 radiocarbon dates could be positioned well on a steep part of the IntCal04 ^{14}C calibration curve (Fig. 7). For subset 2, a high accumulation rate (5.5 yr/cm) was calculated. The match of these 7 radiocarbon dates with the 9600–9500 ^{14}C plateau is not perfect, since there are two outliers (Fig. 7). From this site a WMD-based chronology could be obtained from ca 11 370 to 10 800 cal BP. The WMD approach failed prior to 11 370 cal BP.

4.2.2. Borchert

Due to the absence of datable macrofossils, ^{14}C measurements could not be obtained from the Younger Dryas part of the record. A series of 23 AMS ^{14}C dates (Table 3) was measured from the Preboreal part and initially wiggle-matched (van der Plicht et al., 2004) to the IntCal98 ^{14}C calibration curve (Stuiver et al., 1998). Recently, however, a new calibration curve (= IntCal04) became available and for the present paper the radiocarbon dates were wiggle-matched to this new IntCal04 ^{14}C calibration curve (Reimer et al., 2004). An accumulation of 21.5 yr/cm was calculated (Fig. 8). A WMD-based chronology for the record could be obtained from ca 11 420 to 10 770 cal BP. Before 11 420 cal BP, WMD fails and, as in the Lochem-Ampsen site, the absolute time-scale for the Early Holocene from the Borchert record is uncertain. There are, however, other records (i.e., Kreekrak, Haelen) that seem to give a better WMD within this time-interval (see discussion in Section 5.1).

4.2.3. Zutphen

From the Zutphen site only four AMS ^{14}C radiocarbon dates are available (Table 4). Despite the low number, the radiocarbon dates could be matched well to the IntCal04 ^{14}C calibration curve (Fig. 9). An accumulation of 12.3 yr/cm was calculated. A WMD-based chronology for the record could be obtained from 11,200 to 10,730 cal BP.

4.2.4. Kreekrak

In order to convert the eight radiocarbon dates (Table 5) to calendar years, the record was divided into two intervals,

Table 2
AMS radiocarbon dates of the Lochem-Ampsen record

Depth (cm)	Lab. no.	^{14}C age BP	Dated material	$\delta^{13}C$ values
223	GrA-23060	9590±50	*Populus*, 36 bud scales	−27.39
230	GrA-23058	9540±50	*Populus*, 64 bud scales	−27.70
235	GrA-23052	9520±50	*Populus*, 43 bud scales, 2 catkin scales	−27.73
241	GrA-23056	9440±50	*Populus*, 21 bud scales	−28.15
246	GrA-23055	9460±50	*Populus*, 37 bud scales, 17 catkin scales	−27.35
250	GrA-23054	9570±50	*Populus*, 17 bud scales	−27.70
255	GrA-23051	9500±50	*Populus*, 75 bud scales, 6 catkin scales	−27.15
260	GrA-23050	9460±50	*Populus*, 45 bud scales, 4 catkin scales	−26.97
261	GrA-24422	9570±60	*Populus*, 37 bud scales	−27.36
262	GrA-24420	9540±60	*Populus*, ca 45 bud scales	−25.88
263	GrA-24424	9610±60	*Populus*, 46 bud scales	−26.86
264	GrA-24425	9720±60	*Populus*, 48 bud scales, 1 catkin scale	−28.30
265	GrA-23049	9740±50	*Populus*, 72 bud scales, 4 catkin scales	−27.23
270	GrA-23035	10020±70	*Populus*, 31 bud scales, 1 catkin scale	−26.89
275	GrA-23045	9800±60	*Betula alba*, 55 fruits, 13 female catkin scales, 5 male catkin scales, 3 bud scales; *Cirsium* cf. *arvensis*, 1 seed	−26.63
279–280	GrA-23042	9790±60	*Betula alba*, 3 male catkin scales, 22 female catkin scales, 40 fruits, 1 bud scale; *Ranunculus acris/repens*, 1 nutlet	−26.71
285	GrA-23044	9970±60	*Ranunculus acris/repens*, 3 nutlets	−25.71
290	GrA-23041	9750±60	*Betula alba*, 85 fruits, 91 female catkin scales, 6 bud scales; cf. *Betula nana*, 3 fruits, 18 bud scales	−26.41
294	GrA-23036	9930±50	*Betula alba*, 2 twigs, 49 fruits, 35 female catkin scales (mainly bases), 2 male catkin scales, 4 bud scales; *Ranunculus acris/repens*, 1 nutlet	–
300	GrA-23046	9740±60	*Betula alba*, 33 fruits, 21 female catkin scales, 4 male catkin scales; cf. *Betula nana*, 7 fruits, 11 bud scales	–
305	GrA-23034	9820±50	*Betula alba*, 1 twig, 4 male catkin scales, 24 female catkin scales, 24 fruits, 3 bud scales	−28.53
309	GrA-23062	9730±60	*Betula alba*, 35 fruits, 25 female catkin scales, 4 male catkin scales, 3 bud scales; *Betula nana*, 3 bud scales	−28.25

GrA: Radiocarbon Laboratory of the Centre for Isotope Research, Groningen, The Netherlands.

taking a sedimentary hiatus at 14.08 m into account (Bos et al., 2005b). Subsets of ^{14}C dates from the two sections were then wiggle-matched separately on the IntCal98 ^{14}C calibration curve. However, with the availability of the IntCal04 ^{14}C calibration curve, WMD was carried out again using the same two subsets (Fig. 10). For the lower part of the record, the five radiocarbon dates of subset 1 show a good match on the 10,000–9900 ^{14}C BP plateau. For this section an accumulation rate of 13 yr/cm was calculated. This relative high accumulation rate is partly due to the admixing of sand in the basal part of the sequence. In the upper part of the record, the higher total microfossil concentrations indicate that the accumulation rate was lower. For this section an accumulation rate of 20.2 yr/cm was calculated. Despite the low number of radiocarbon dates in subset 2, the three radiocarbon dates could be matched well with the calibration curve, particularly because the uppermost date could be pinpointed on a steep part of the curve. WMD shows that the hiatus corresponds to ca 530 calendar years.

4.2.5. Haelen

Due to the absence of datable material, ^{14}C measurements could not be made from most of the Younger Dryas part. Only the uppermost Younger Dryas sample gave enough terrestrial material for AMS ^{14}C dating. From the Haelen site a series of 28 AMS ^{14}C radiocarbon dates was available (Table 6). The radiocarbon dates were measured in three series and all outliers (10) belong to the first series (total of 17). This may suggest an error due to an unknown sample treatment problem. However, WMD excluding the whole first series of radiocarbon dates gave a similar match on the IntCal04 ^{14}C calibration curve as WMD in which all radiocarbon dates were used (Fig. 11). An accumulation of 10.3 yr/cm was calculated. A WMD-based chronology for the record could be obtained from ca 11,520 to 10,530 cal BP.

4.3. LOI results

In comparison to the quite uniform lithological record, the LOI curve of the Lochem-Ampsen record shows considerable changes (Fig. 2). The curve increases during the Friesland Phase (transition from sand to sandy peat to peat). During the Rammelbeek Phase there are two distinct minima in the LOI values, the first one early in the Rammelbeek Phase is lower than the second one during the end of the Rammelbeek. Only the first minimum corresponds with a visible change to sandy peat. During the Late Preboreal, the LOI values increase to around 85% and only minor oscillations are recorded.

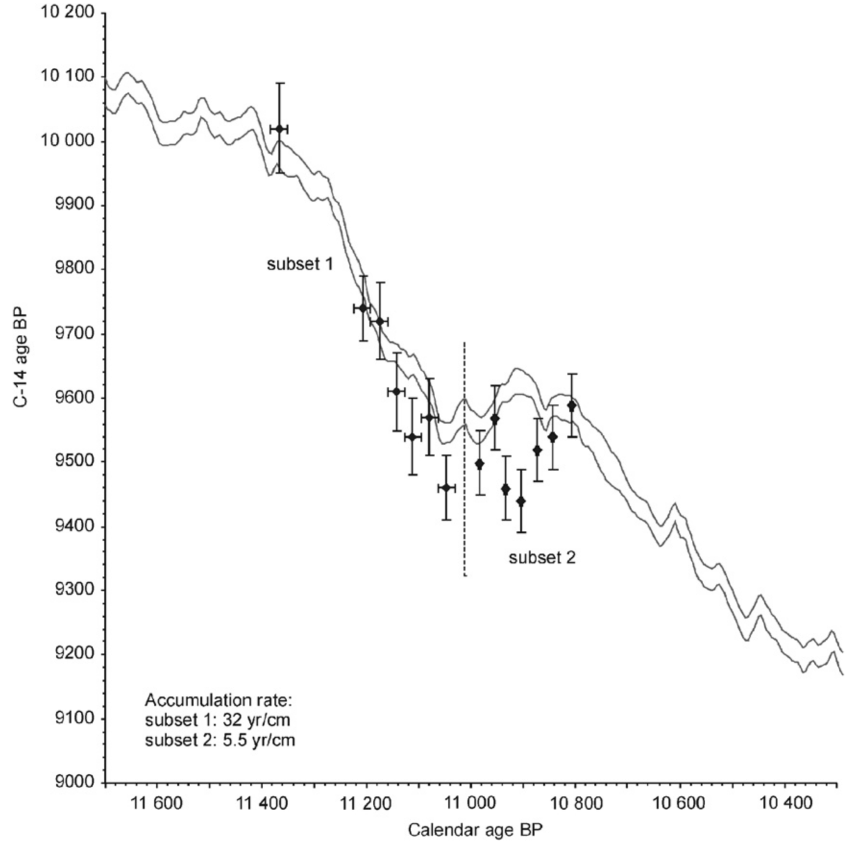

Fig. 7. WMD of the Lochem-Ampsen record.

Table 3
AMS radiocarbon dates of the Borchert record

Depth (cm)	Lab. no.	^{14}C age BP	Dated material	$\delta^{13}C$ values
491.2	GrA-17590	9550±60	*Pinus* + *Betula*	−25.7
492.8	GrA-17588	9480±60	*Pinus* + *Betula*	−26.31
494.4	GrA-17578	9520±60	*Pinus* + *Betula*	−26.32
496.0	GrA-17577	9530±70	*Pinus* + *Betula*	−26.76
497.6	GrA-17456	9600±60	*Betula*	−27.05
499.2	GrA-17576	9490±60	*Betula*	−26.72
500.8	GrA-17455	9610±50	*Betula*	−26.52
502.4	GrA-17453	9600±50	*Betula*	−26.7
504.8	GrA-17575	9530±60	*Betula*	−27.44
507.2	GrA-1715	9650±50	*Betula* + *Populus*	−26.14
508.8	GrA-1717	9700±50	*Betula* + *Populus*	−26.74
510.4	GrA-1718	9790±50	*Betula* + *Populus*	−25.99
513.6	GrA-2623	9900±60	Mosses	−28.28
513.6	GrA-2654	10200±200	*Betula*	−26.83
514.4	GrA-1711	9830±50	*Betula* + Mosses	−25.69
516.0	GrA-1714	9860±50	*Betula*	−25.78
517.6	GrA-1712	9740±50	*Betula* + Mosses	−25.72
518.4	GrA-2621	10050±60	Mosses	−28.09
518.4	GrA-2643	10070±100	*Betula*	−27.21
520.0	GrA-2792	10400±800	*Betula*	−27.23
520.0	GrA-2620	9990±60	Mosses	−32.89
521.6	GrA-1716	9900±50	*Betula*	−25.98
523.2	GrA-1713	9860±50	*Betula*	−27.54

GrA: Radiocarbon Laboratory of the Centre for Isotope Research, Groningen, The Netherlands.

In the Kreekrak record the LOI curve (Fig. 5) shows an increase at the start of the Friesland Phase. This is simultaneous with the transition from sand to sandy, light yellow-brown gyttja. During the Friesland Phase, the LOI values increase more or less continuously, but there is a small decrease during the Rammelbeek Phase. This decrease is coincident with a change to a lighter coloured deposit. At the start of the Boreal, the LOI values show a major increase.

In the Haelen record the LOI values (Fig. 6) show a strong increase at the start of the Friesland Phase. This increase is followed by a major drop in the values at 387 cm, where a sandy layer is present. After this drop, the LOI values return to earlier levels. A first small minimum is present around the Friesland/Rammelbeek transition and a second minimum at the end of the Rammelbeek Phase. This phenomenon was also observed at the Lochem-Ampsen site. During the Late Preboreal the LOI values increase only slightly and minor oscillations are recorded (Fig. 6).

5. Discussion

5.1. Wiggle-match dating

The WMD results of the five sites demonstrate that WMD during the investigated time-interval can give an

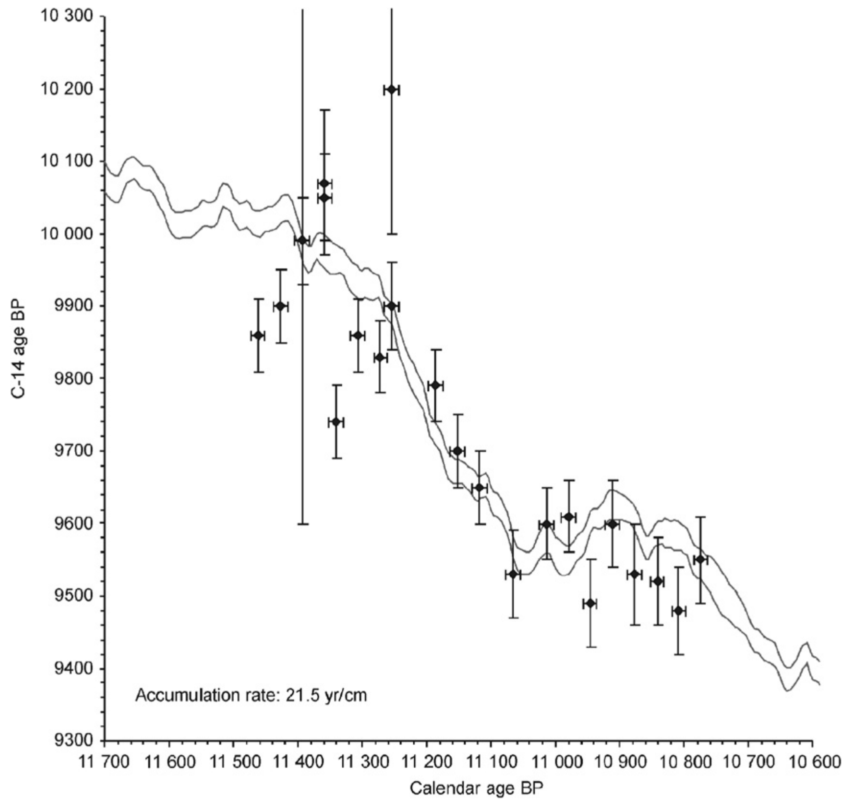

Fig. 8. WMD of the Borchert record.

Table 4
AMS radiocarbon dates of the Zutphen record

Depth (cm)	Lab no.	^{14}C age BP	Dated material	$\delta^{13}C$ values
33	GrA-21040	9430 ± 50	17 *Betula* female catkin scales, 4 *Populus* bud scales	−27.13
42	GrA-17591	9620 ± 60	19 *Betula* fruits, 5 *Betula* female catkin scales, 2 *Carex* sp. nutlets, 10 *Lycopus europaeus* fruits, 1 *Rumex* sp. seed fragment, 6 *Betula*/*Populus* bud scales, leaf remains of *Betula* or *Populus*	−27.11
46	GrA-17592	9670 ± 60	55 *Betula* fruits, 16 *Betula* female catkin scales, 1 *Carex* sp. nutlet and perigynium, 5 *Lycopus europaeus* fruits, 1 *Rumex* sp. fruits, 2 *Populus* bud scales, 2 *Betula* bud scales, leaf remains of *Betula* or *Populus*, 1 Poaceae caryopsis	−27.54
76	GrA-21033	9760 ± 70	14 *Betula* fruits, 2 *Betula* female catkin scales, $2\frac{1}{4}$ *Betula* bud scales, 3 *Salix* bud scales, 4 *Populus* catkin scales, 1 *Populus* bud scale, $\frac{1}{2}$ *Rubus* fruitstone	−28.14

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accurate chronology, which is essential for the comparison with other high-resolution records, in particular, the Greenland ice-core record. Furthermore, it has been shown that if the position of the radiocarbon dates is well chosen and the biostratigraphy, LOI and lithology of the record are taken into consideration, WMD also can be successful with a small number of ^{14}C dates (i.e., Kreekrak, Zutphen).

Moreover, the WMD results of the five sites also demonstrate that WMD in this time-interval encounters problems. First of all, the two large radiocarbon plateaux at 10 000–9900 and 9600–9500 ^{14}C BP remain a problem because they reflect a relatively long time-interval and therefore a large number of radiocarbon dates is needed to cover these plateaux (Blaauw et al., 2004). Also it was often difficult to find datable, terrestrial macrofossils from deposits spanning the late Younger Dryas and Lateglacial/Holocene (= LG/H) transition.

Secondly, the WMD computer software (van der Plicht, 1993, updated with later calibration curves) that was used assumes a linear accumulation rate. In most Dutch Early Holocene sites, however, limnic deposits are rapidly succeeded by telmatic and terrestrial peat deposits. The sedimentological changes are strongly related to the major climatic changes and oscillations that occurred within this period. With the sedimentological shifts the accumulation rates also vary. Furthermore, accumulation rates appeared to be non-linear even within one sediment type, e.g., in the Lochem-Ampsen peat deposits, the accumulation rate at

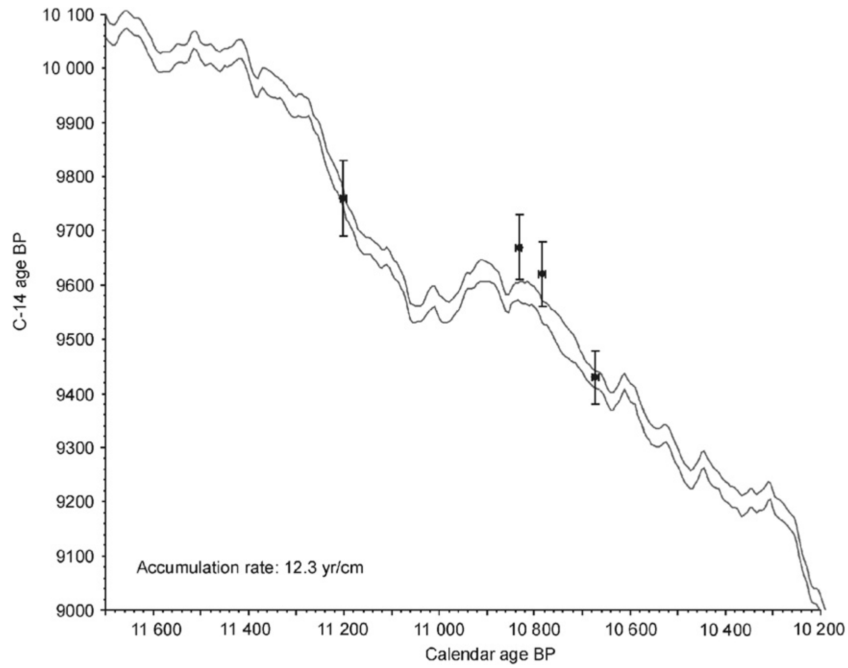

Fig. 9. WMD of the Zutphen record.

Table 5
AMS radiocarbon dates of the Kreekrak record

Depth (m)	Lab. no.	^{14}C age BP	Dated material	δ^{13}C values
13.825–13.855	UtC-9217	9080 ± 60	*Cornus mas*, 2 nut fragments; *Carex rostrata*, 1 nutlet; *Carex* sp. 5 nutlets; *Urtica dioica*, 8 fruits; *Menyanthes trifoliata*, 2 seeds; *Oenanthe aquatica*, 1 fruit; unidentified leaf remains	−28.1
14.045	GrA-23040	9450 ± 60	*Betula*, 37 fruits, 2 bud scales, 3 male catkin scales	–
14.075	GrA-23039	9490 ± 50	*Betula*, 57 fruits, 15 female catkin scales, 14 male catkin scales	−28.53
14.085	GrA-23030	9950 ± 50	*Betula*, 50 female catkin scales	−28.01
14.155	GrA-23031	10030 ± 50	*Betula*, 50 female catkin scales	−28.53
14.195	UtC-9125	9930 ± 50	*Betula*, 512 fruits, 105 female catkin scales, 1 bud, 3 bud scales; *Atriplex*, 1 seed; *Lycopus europaeus*, 1 fruit; *Nymphaea alba*, 13 seeds; *Ceratophyllum demersum*, 4 fruits	−27.7
14.225	GrA-23032	10060 ± 50	*Betula*, 40 female catkin scales	−28.54
14.275	GrA-23029	10140 ± 60	*Betula*, 2 small twigs, 19 fruits, 5 females catkin scales, 2 males catkin scales, 1 bud scale	–

Laboratory no. Utc: Van de Graaff Laboratory, Utrecht, The Netherlands, GrA: Radiocarbon Laboratory of the Centre for Isotope Research, Groningen, The Netherlands.

the end of the Rammelbeek Phase initially decreased, but increased at the start of the Late Preboreal. This evidence for changing accumulation rates is apparent from the botanical data and LOI curve, but not visible in the sediments. In statistically based software programs for WMD, such as Bpeat (Blaauw and Christen, 2005), non-linear changes in accumulation rate are not taken into account. An alternative for visual WMD can be Bayesian sequence modelling or a combination of Bayesian analysis and WMD (Blockley et al., 2004, 2007; Blaauw and Christen, 2005). Bayesian analysis of radiocarbon chronologies recognises the stratigraphical succession of the samples from which the radiocarbon dates were obtained. The Bayesian sequence modelling of the Oxcal software (Bronk Ramsey, 1999, 2001) also can deal with non-linear accumulation rates. We attempted both WMD in Bpeat as well as Bayesian sequence modelling in Oxcal in order to acquire a reliable chronology for our Dutch datasets. In our records, however, the sediment and accumulation rates changed frequently, which probably caused these methods to be unsuccessful.

A third problem is connected with the material itself that was used for radiocarbon dating. It appears that terrestrial material also can give ‘wrong’ dates, i.e., outliers in the radiocarbon ages of the samples that are so large that they cannot be explained by the wiggles in the calibration curve. In the series from the Borchert and Lochem-Ampsen sites there are many outliers (Figs. 7 and 8). In comparison to

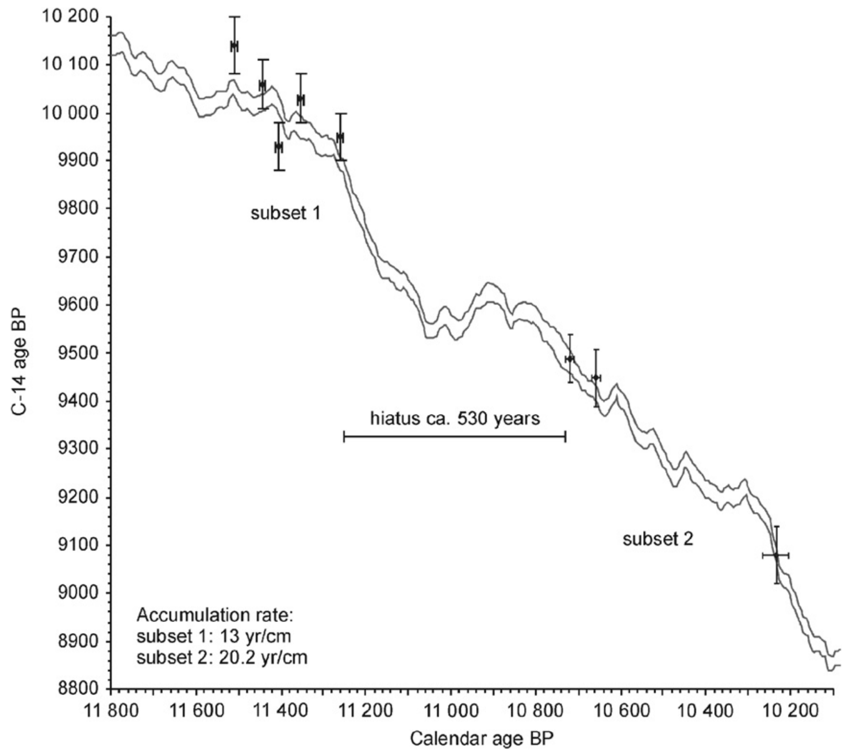

Fig. 10. WMD of the Kreekrak record.

their expected age based on biostratigraphical correlation with the Dutch Lateglacial–Early Holocene biostratigraphy and chronostratigraphy (Hoek, 1997a), the majority of these dates is clearly too young. A possible younging effect that may relate to storage time and contamination from fungal growth (Wohlfarth et al., 1998) is unlikely since fungi do not use CO_2 from the air. Translocation of terrestrial macroremains (e.g., *Betula*, *Populus*) by reworking, bioturbation or other physical processes (Turney et al., 2000) seems also unlikely, since the material used for ^{14}C dating was not fragmented or badly preserved. Moreover, the majority of the outliers is found in the late Younger Dryas and early Preboreal deposits. This is the period of the 10,000–9900 ^{14}C plateau. At the sites where relatively deep, open water was present during the Preboreal (Haelen and Kreekrak, Figs. 10 and 11), there are fewer outliers than at the sites (Lochem-Ampsen and Borchert, Figs. 7 and 8) where the process of hydroseral succession was more advanced and relatively shallow water conditions prevailed. Also from other Dutch sites where telmatic water conditions were present during the Preboreal, radiocarbon dates are present that are too young (Bohncke, unpublished data). Other possible processes can be downward percolation of humic acids or depletion of the natural ^{14}C (e.g., Turney et al., 2000; Walker et al., 2003). Downward percolation of humic acids causes a younging effect and may constitute to a potential source of contamination in the Early Holocene, especially where limnic sediments grade rapidly upwards into telmatic and terrestrial peats. Depletion of the natural ^{14}C content causes an aging effect of the dated material. These processes, however, usually only play a role in bulk samples. In case one or more of the above mentioned processes (e.g., translocation of macroremains, downward percolation of humic acids or depletion of natural ^{14}C) occurred during or after the deposition of our sediments, it is remarkable that dates that are assumed 'too young' are alternated by dates that seem to fit well with the expected age based on biostratigraphical correlation, especially because all dates are based on selected macroremains of the same taxa (i.e., *Betula*, *Populus*). However, this still leaves us without a satisfactionary explanation for the dates that are too young.

5.2. Botanical and climatological aspects

The Dutch records, covering the LG/H transition and Preboreal, reflect a period during which major climatic changes occurred on a northern Atlantic scale. The LG/H transition is characterised by abrupt warming, followed by a climatic oscillation, the Preboreal oscillation (PBO) (Björck et al., 1996). These events are recorded in detail in various varved European terrestrial records (Lotter et al., 1992; Goslar et al., 1993; Merkt and Müller, 1999; Litt et al., 2003) and in the $\delta^{18}O$ records of the Greenland ice cores (Dansgaard et al., 1993; Grootes et al., 1993; Johnsen et al., 1997; North Greenland Ice Core Project members, 2004; Rasmussen et al., 2006). In order to compare environmental and climatic change the five ^{14}C wiggle-match dated regional pollen diagrams were tentatively compared with the $\delta^{18}O$ curve in the ice core

Table 6
AMS radiocarbon dates of the Haelen record

Depth (cm)	Series no.	Lab. no.	^{14}C age BP	Dated material	$\delta^{13}C$ values
293	2	GrA-26051	9380±60	*Betula alba*, 20 fruits, 8 female catkin scales, 2 male catkin scales, 1 bud scale; Pinus, 8 scale leaves	−27.93
299	2	GrA-26052	9530±70	*Betula alba*, 4 fruits, 13 female scale leaves	−27.35
303	1	GrA-25203	9490±50	*Betula alba*, 5 female catkin scales; *Pinus*, 8 scale leaves	−28.38
304	3	KIA-20867	9320±45	Selected macroremains	–
309	2	GrA-26053	9410±60	*Betula alba*, 1 female catkin scale, 10 fruits, *Pinus*, 9 scale leaves, 1 needle	−28.36
311	1	GrA-25201	9500±60	*Pinus*, 14 scale leaves	−27.98
313	2	GrA-26055	9500±60	*Betula alba*, 14 fruits, 2 female catkin scales, 1 bud scale; *Populus*, 1 catkin scale, 2 bud scales	−28.96
320	1	GrA-25200	9440±50	*Betula alba*, 7 fruits, 13 female catkin scales, 1 male catkin scale	−27.99
325	1	GrA-25197	9420±60	*Betula alba*, 18 fruits, 2 female catkin scales, 1 male catkin scale	−28.47
330	1	GrA-25196	9450±60	*Betula alba*, 41 fruits, 15 female catkin scales, 2 bud scales	−28.69
335	1	GrA-25387	9480±70	*Betula alba*, 20 fruits, 4 female catkin scales, 1 bud scale	−28.15
340	1	GrA-25385	9180±60	*Betula alba*, 17 fruits, 4 female catkin scales, 3 bud scales	−27.82
341	2	GrA-26056	9460±60	*Betula alba*, 24 fruits, $4\frac{1}{2}$ female catkin scales, 1 male catkin scale, 3 bud scales; *Populus*, $\frac{1}{4}$ bud scale	−28.19
345	1	GrA-25384	9470±70	*Betula alba*, 14 fruits, 4 female catkin scales; *Populus*, 1 catkin scale	−28.32
350	1	GrA-25382	9330±60	*Betula alba*, 46 fruits, 1 female catkin scale, 1 budscale	−28.29
353	2	GrA-26058	9730±70	*Betula alba*, 20 fruits, 2 female catkin scales, 1 bud scale	−31.86
355	1	GrA-25381	9810±80	*Betula alba*, 11 fruits, 3 female catkin scales, 1 male catkin scale, 2 bud scales; *Populus*, 1 catkin scale	−28.82
360	1	GrA-25365	9800±80	*Betula alba*, 12 fruits, 4 female catkin scales, 3 male catkin scales, 2 bud scales	−28.54
363	2	GrA-26059	10 000±80	*Betula alba*, 4 fruits, 4 female catkin scales	−27.42
365	1	GrA-25364	9590±70	*Betula alba*, 5 fruits, 3 female catkin scales, 1 male catkin scale; *Populus*, $1\frac{1}{2}$ catkin scale	−28.01
370	1	GrA-25363	9500±60	*Betula alba*, 5 fruits, 2 female catkin scales	−29.43
373	2	GrA-26061	9970±70	*Betula alba*; 5 fruits, $3\frac{1}{2}$ female catkin scales	−29.04
375	1	GrA-25362	9900±60	*Betula alba*, 6 fruits, 3 female catkin scales	−27.51
380	1	GrA-25359	9210±60	*Betula alba*, 17 fruits, 7 female catkin scales, 1 male catkin scale	−27.10
381	3	KIA-20893	9955±45	–	–
382	2	GrA-26062	10 100±90	*Betula alba*, 17 fruits, 4 female catkin scales, 2 bud scales	−27.84
386	1	GrA-24358	9410±70	*Betula alba*, 12 fruits, 4 female catkin scales	−27.23
389–390	2	GrA-26063	10 040±80	*Betula alba*, 11 fruits, $4\frac{1}{2}$ female catkin scales, 2 male catkin scales, $\frac{1}{2}$ bud scale; *Betula nana*, 1 fruit, 1 bud scale	−28.51

GrA: Radiocarbon Laboratory of the Centre for Isotope Research, Groningen, The Netherlands. KIA: Leibniz-Labor, Kiel, Germany.

records (Figs. 12 and 13). It appears that trends recorded in the five records and in the $\delta^{18}O$ curve are approximately synchronous, which suggest that environmental changes as reflected in our sediments cores were primarily influenced by major, climatic changes.

In two Dutch records, i.e., Kreekrak and Haelen, the start of the Friesland Phase (LG/H transition) was dated between 11,530 and 11,500 cal BP (Table 7 and Fig. 12). The transition is coincident with a change to more organic-rich deposits. This is also reflected in a rise in the LOI curve at the start of the Preboreal and indicates an increase in biological productivity. The Friesland Phase is characterised by a strong expansion of boreal birch forests and was a period of rising mean summer temperatures (van Geel et al., 1981). During this phase minimum mean July temperatures quickly rose from 12–13 °C (i.e., *Typha latifolia*, *Potamogeton mucronatus* and *Sanguisorba minor*) to 13–16 °C (i.e., *Typha angustifolia*, *P. mucronatus*, *Solanum dulcamara*, *Scirpus lacustris*, *Ceratophyllum demersum* and *Lycopus europaeus*) (Table 2). A short cooler interval resulting in an opening of birch forest within this early Preboreal warming phase is suggested by Bohncke and Hoek (2007), who interpreted a negative excursion in the $\delta^{18}O$ values during the Friesland Phase in the Dutch lake carbonate record of Kingbeekdal. A gradual increase in the water level recorded at many locations—e.g., Kreekrak, Borchert and Haelen—suggests that the increase in temperature coincided with an increase in precipitation (see also Hoek and Bohncke, 2002). Higher lake water levels between 11,450 and 11,400 cal BP have also been reported from elsewhere in west-central Europe (Magny et al., 2007). CO_2 concentrations reconstructed from fossil birch leaves from the Borchert record indicate a sharp rise in the atmospheric CO_2 during this period (Wagner et al., 1999).

Comparison of the GRIP-ss08c chronology (on the GRIP-INTIMATE time-scale, Björck et al., 1998; Walker et al., 1999) and the vegetation development in The

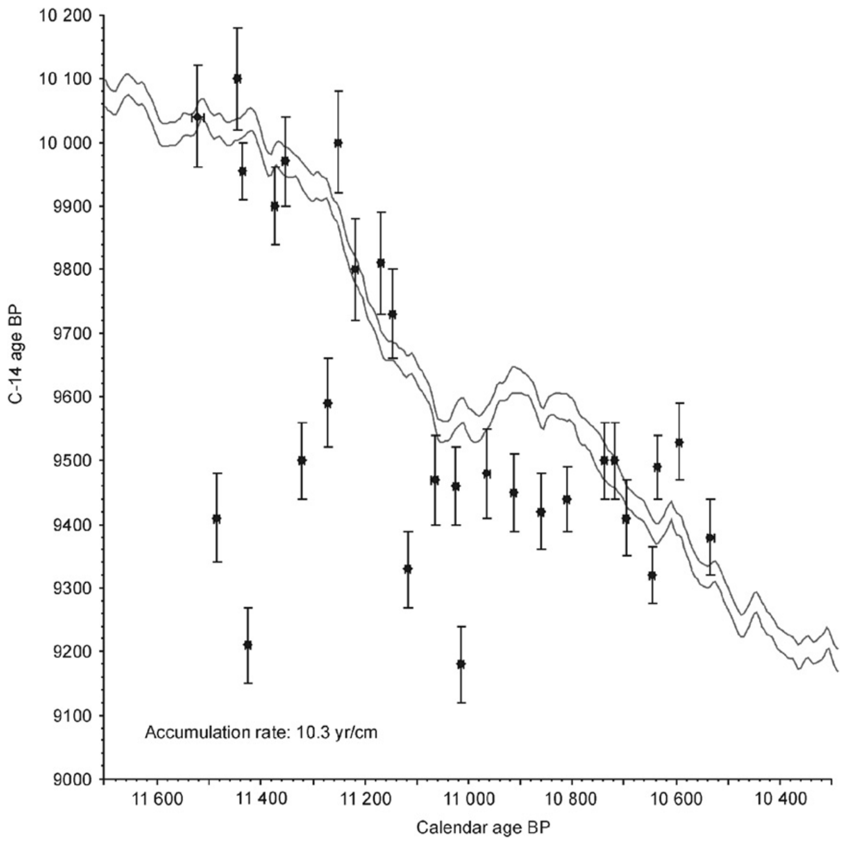

Fig. 11. WMD of the Haelen record.

Netherlands (Hoek, 2001) earlier suggested that there was no time-lag between the climate warming and the vegetation response at the LG/H transition. During the Early Holocene, forest stands were relatively near, relict permafrost did not occur; therefore vegetation could recover quickly after the climatic improvement (Hoek, 2001). In the new ice core chronology for the three Greenland ice cores, the DYE-3, GRIP and NGRIP, the LG/H transition is dated at 11.7 ka b2k (i.e., before 2000 AD, thus corresponding with 11,650 cal BP) (Rasmussen et al., 2006). This would indicate a much longer time-lag, ca 120–150 years, between the vegetation response and the climate warming (Fig. 13). This seems rather unrealistic. Then again, the dendrochronological time-scale and Greenland ice core time-scale are based on different proxy records and therefore do not have to be comparable. Assuming that the northern Atlantic temperature changes were recorded without a time-lag, the best way to compare terrestrial and Greenland ice-core chronologies is probably by comparison of $\delta^{18}O$ in lake carbonates with the $\delta^{18}O$ record in Greenland ice, i.e., oxygen-isotope wiggle matching. However, in studies where pollen analysis was combined with $\delta^{18}O$ measurements in lake carbonates (e.g., Lotter et al., 1992; Goslar et al., 1993; Hammarlund et al., 1999; Schwander et al., 2000; Hoek and Bohncke, 2001; Bohncke and Hoek, 2007), no such long time-lag was recorded between the climate warming and the vegetation response at the LG/H transition.

The Rammelbeek Phase started around 11 430–11 350 cal BP (Table 7 and Fig. 12). Forest expansion was interrupted and grasses dominated the regional vegetation. The LOI curves show one or two major minima during this phase. This is probably related to a sedimentological change (e.g., higher minerogenic content), which may have had several causes, i.e., a decrease in the biological productivity, a lowering of the water table and/or an increase in aeolian activity due to a less forested, more open landscape with soils not completely covered by vegetation. Shifts in the aquatic and telmatic taxa in the Kreekrak, Haelen and Lochem-Ampsen diagrams indicate a lowering of the water table. Lower groundwater levels during the Rammelbeek Phase in The Netherlands were also suggested by others (Hoek, 1997a; Hoek and Bohncke, 2002). Both the steppe-like vegetation and lower groundwater levels indicate that during the Rammelbeek Phase the climate was dry and continental, probably with warm summers and cold winters (van Geel and Kolstrup, 1978; van Geel et al., 1981). For this phase, minimum mean July temperatures around 13–15 °C were suggested, although the presence of seeds, respectively, fruits of *T. angustifolia*, *Oenanthe aquatica*, *C. demersum*, and *L. europaeus* at the investigated sites indicates that mean July temperatures were at least 14–16 °C (Table 2). In many of the Dutch palynological records the drier Rammelbeek Phase is absent or not recognised (see low number of records in Fig. 1). The lower groundwater levels

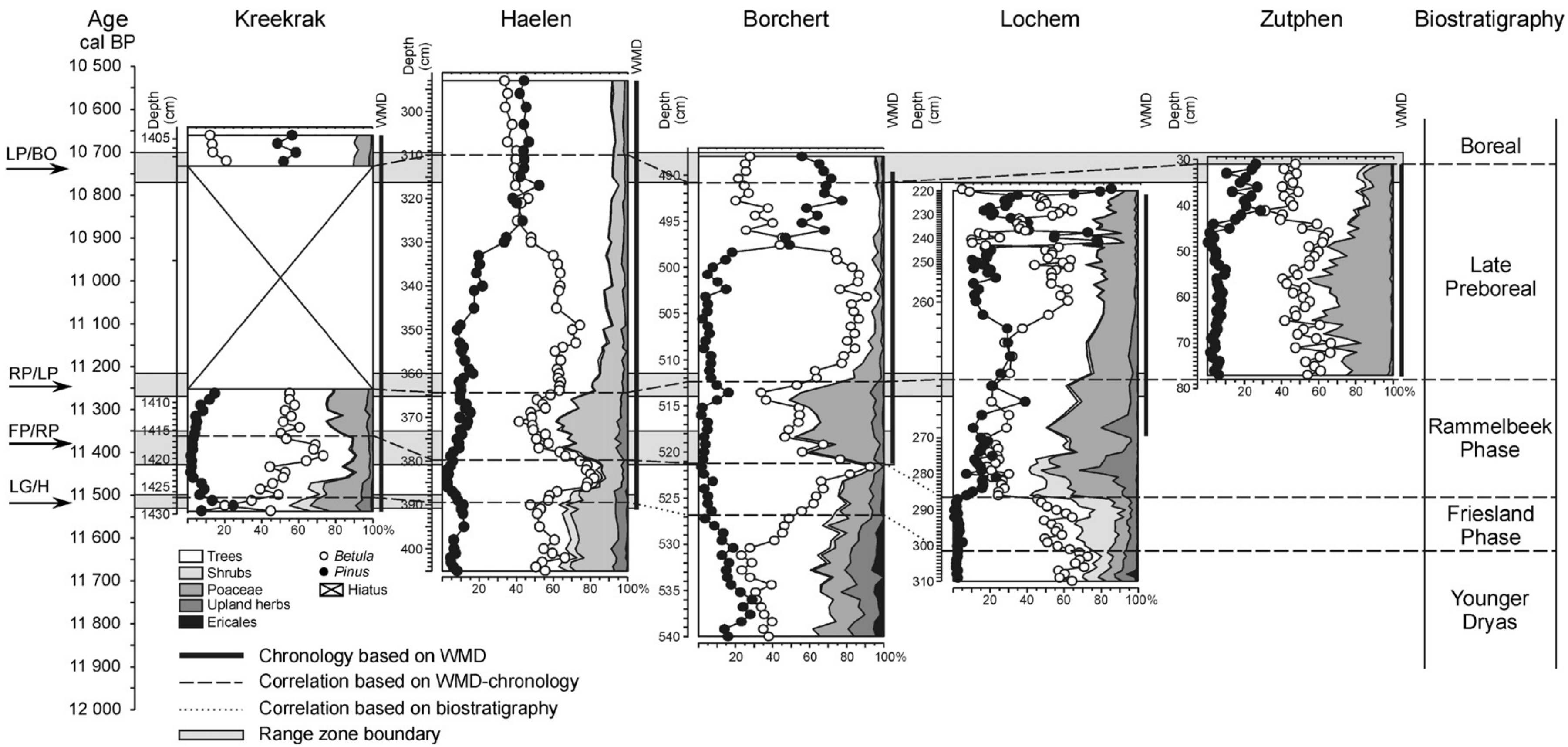

Fig. 12. Correlation of the summary pollen diagrams of the five Dutch records. On the vertical axis the calibrated time-scale in years cal BP is displayed. Transition: LG/H = Lateglacial/Holocene, FP/RP = Friesland Phase/Rammelbeek Phase, RP/LP = Rammelbeek Phase/Late Preboreal, LP/BO = Late Preboreal/Boreal.

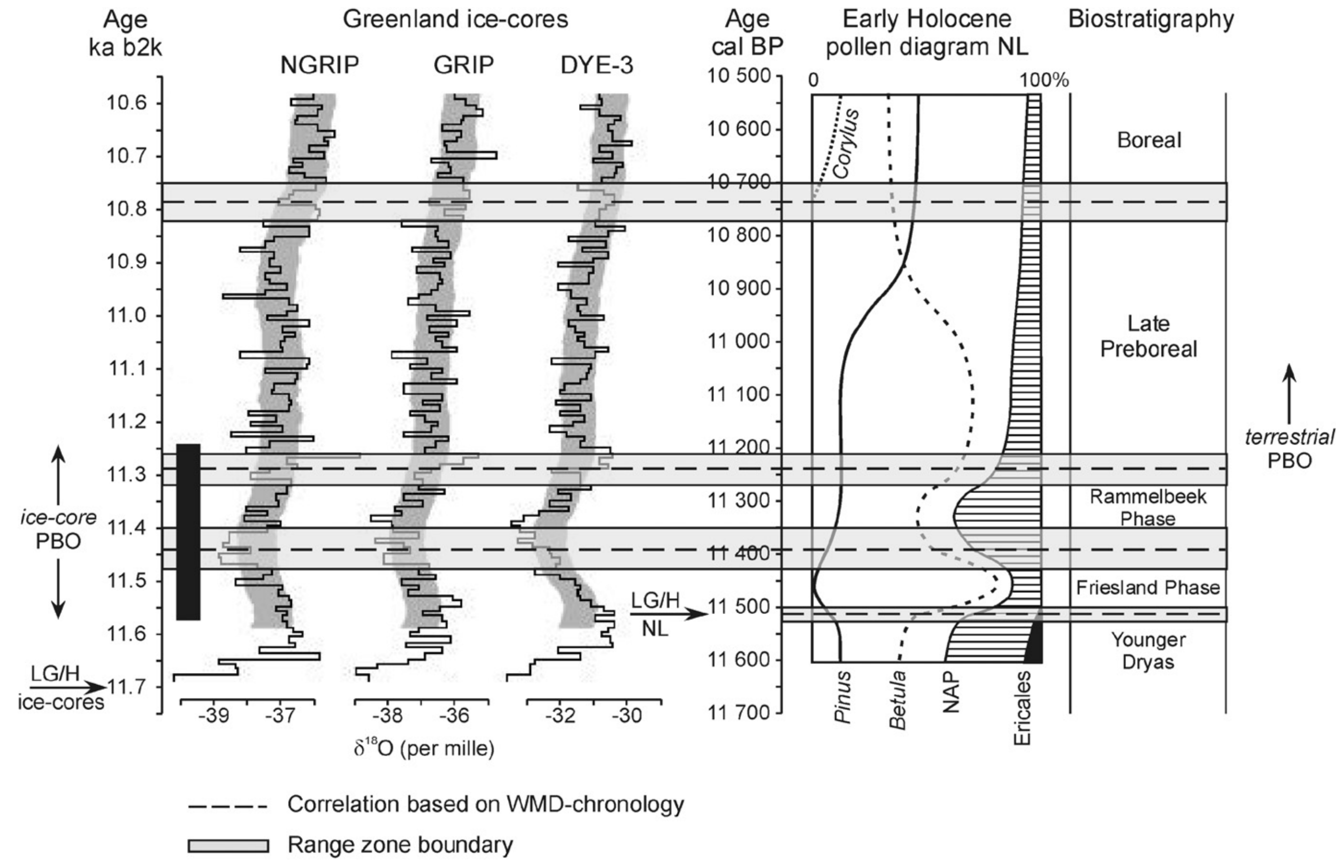

Fig. 13. Schematic Early Holocene pollen diagram for The Netherlands on the calibrated time-scale (age in cal BP), compared with the new ice core chronology for the three Greenland DYE-3, GRIP and NGRIP ice cores (age in ka 2bk) (Rasmussen et al., 2007). Indicated are the Lateglacial/Holocene transition (LG/H) in the ice-cores and Dutch terrestrial sites, the *ice-core PBO* and *terrestrial PBO*.

Table 7
WMD dated zone boundaries (in cal BP) in the five Dutch records

	Lochem-Ampsen	Borchert	Zutphen	Kreekrak	Haelen	WMD age
LP/BO	–	10 765 ± 11	*10 727 ± 5*	*10 731 ± 10*	10 708 ± 5	10 770–10 700
Pine	10 930 ± 3	10 910 ± 11	10 874 ± 5	–	11 170 ± 5	11 170–10 870
RP/LP	11 224 ± 16	11 229 ± 11	–	*11 255 ± 6.5*	11 266 ± 5	11 270–11 210
FP/RP	–	11 418 ± 11	–	11 359.5 ± 6.5	11 420 ± 5	11 430–11 350
LG/H	–	–	–	11 502.5 ± 6.5	11 522 ± 10	11 530–11 500

Transition: LG/H = Lateglacial/Holocene, FP/RP = Friesland Phase/Rammelbeek Phase, RP/LP = Rammelbeek Phase/Late Preboreal, LP/BO = Late Preboreal/Boreal. Pine = timing of the pine expansion. In *Italics* the ages of zone boundaries are given that may not be accurate because they are bordered by a hiatus.

during this phase, however, also may have been related with river incision (Hoek and Bohncke, 2002; Bohncke and Hoek, 2007).

Comparison between the Dutch records and the new ice core chronology (Rasmussen et al., 2007) shows that the start of the Rammelbeek Phase is synchronous with the coldest part (approximately 100 years, 11.5–11.4 ka b2k) of a negative excursion in ice-core $\delta^{18}O$ values, the so-called Preboreal oscillation or PBO (Björck et al., 1996) (Fig. 13). The PBO in the Greenland ice core records is a phase of diminished snow accumulation that has been attributed to a meltwater flux, caused by the melting of the Scandinavian ice sheets, including the drainage of the Baltic Ice Lake (e.g., Björck et al., 1997; Hald and Hagen, 1998; Husum and Hald, 2002) and drainage of Lake Agassiz (e.g., Fisher et al., 2002; Teller et al., 2002). This resulted in a temporary decrease in the North Atlantic thermohaline circulation, causing a colder climate. The NW European terrestrial equivalent of this cool climatic phase may have been dry and continental, i.e., the Rammelbeek Phase (van der Plicht et al., 2004). The Rammelbeek phase is thus assumed to be contemporaneous with the coldest part of the "*ice-core PBO*" in the Greenland ice cores (van der Plicht et al., 2004; Bos et al., 2005b) (Fig. 13).

The Rammelbeek Phase was followed between 11 270 and 11 210 cal BP by the Late Preboreal (Table 7 and Fig. 12), when birch forests expanded again and *Populus* became more abundant. LOI values increase again. The botanical data (*T. angustifolia*, *O. aquatica*, *C. demersum* and *L. europaeus*) suggest that minimum mean July temperatures remained around 14–16 °C (Table 2). Local *Sphagnum* peat growth and higher lake water tables (van Geel et al., 1981; Hoek and Bohncke, 2002) are probably indications for a sudden change to a more humid climate. Higher lake water levels, recorded in a large number of European lakes, also indicate wetter climatic conditions between 11 300 and 11 150 cal BP in west-central Europe, while a marked climatic drying occurred in north-central Italy, Spain and southern Norway (Fig. 8 in Magny et al., 2007). The change to a wetter climate in The Netherlands at the start of the Late Preboreal was probably triggered by a sudden decline in solar activity, which is evident from the simultaneous increase in the cosmogenic nuclides ^{14}C and ^{10}Be (van der Plicht et al., 2004). Solar irradiance changes, however, are assumed to be relatively small and it is suggested that an amplifying mechanism is required to account for the magnitude of the climate changes (Rind, 2002). Coupled climate model simulations of Holocene cooling events recently showed that solar forcing triggers oceanic feedback, i.e., the oceans thus may have played an important role in amplifying centennial-scale climate variability (Renssen et al., 2006).

The start of the Late Preboreal is synchronous with the end of the PBO in the Greenland ice core records, i.e., 11,270–11,280 b2k (Rasmussen et al., 2007), which corresponds to 11,220–11,230 cal BP (Fig. 13). During this period, the $\delta^{18}O$ isotope values in the Greenland ice core records rise again and return to normal interglacial conditions. This phase, characterised by the rise in cosmogenic nuclides (^{14}C, ^{10}Be) and by a further shift in $\delta^{18}O$, can be correlated with the "*terrestrial PBO*" as defined by Björck et al. (1997) in the North Atlantic record (van der Plicht et al., 2004) (Fig. 13). CO_2 concentrations reconstructed from fossil birch leaves from the Borchert site show a gradual decline at the start of the Late Preboreal, followed by a marked increase. *Pinus* expanded during the later part of the Late Preboreal, around 11 170–10 820 cal BP (Table 7 and Fig. 12).

The onset of the Boreal was characterised by the immigration of *Corylus* and dates between 10 770 and 10 700 cal BP (Table 7 and Fig. 12). During this period, relatively dense woodlands developed in The Netherlands with hazel, oak, elm and pine.

5.3. Future prospects

From the investigated sites some research is still in progress. The Preboreal record of the Lochem-Ampsen site revealed numerous remains of leaves of birch (and probably some buckthorn), which can be used for stomatal frequency analysis. The leaf material is currently under investigation (Dr. F. Wagner, Utrecht University) and may give an additional CO_2 curve that can be compared with the present one from the Borchert record (Wagner et al., 1999).

The Preboreal deposits of the Haelen and Lochem-Ampsen sites are under examination for the presence of microtephra (Dr. S. Davies, University of Swansea). Hopefully some microtephra layers are present that can be used as chronological marker horizons to enable mutual correlation of the Dutch records with other records, in particular the Greenland ice core record. Recently, tephrochronological research revealed the presence of microscopic tephra layers in Lateglacial deposits in The Netherlands (Davies et al., 2005). For the Early Holocene several microtephras are now known from NW Europe (Merkt et al., 1993; Pyne-O'Donnell, 2007). Some of these also may be discovered in The Netherlands.

5.4. Conclusions

WMD of ^{14}C samples reflecting the LG/H transition and Early Holocene can give an accurate chronology. If the position of the radiocarbon dates is well chosen and the biostratigraphy, LOI and lithology of the record are taken into consideration, WMD can be successful with a small number of ^{14}C dates. However, WMD in this time-interval also encounters problems which are related to:

(1) The two large radiocarbon plateaux. Due to these plateaux a large number of radiocarbon dates is needed. Datable terrestrial material from deposits spanning the LG/H transition was often absent.
(2) The terrestrial material also can give 'wrong' dates, i.e., outliers in the radiocarbon ages of the samples that are too large to be explained by wiggles in the calibration curve.
(3) The presently available WMD software is of limited value because of the unrealistic presumption of linear sediment accumulation rates.

Detailed high-resolution multi-proxy analyses (including microfossils, macroremains, LOI measurements and AMS ^{14}C WMD) of five Dutch Preboreal records showed that, following the Lateglacial/Holocene climate warming, birch woodlands expanded around 11 530–11 500 cal BP during the Friesland Phase of the Preboreal. Following the Friesland Phase, two distinct climatic shifts could be inferred:

(1) Around 11,430–11,350 cal BP the expansion of birch forests was interrupted by a dry continental phase with open grassland vegetation, the Rammelbeek Phase. The start of this phase was coeval with the coldest part of the Preboreal oscillation (i.e., *ice-core PBO*) as observed in the $\delta^{18}O$ record of the Greenland ice-core records and was probably caused by a large meltwater flux that resulted in a temporary decrease of the thermohaline circulation in the North Atlantic.

(2) At the start of the Late Preboreal, at ca 11,270–11,210 cal BP, a sudden shift to a more humid climate occurred and birch forests expanded again, followed later by pine. This phase was coeval with the PBO in the North Atlantic terrestrial records (i.e., *terrestrial PBO*). A simultaneous increase in the cosmogenic nuclides ^{14}C and ^{10}Be suggests that these changes in climate and vegetation were forced by a sudden decline in solar activity.

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